Energy sector contribution to regional climate action: The case of Latin America

Sébastien Postic, Sandrine Selosse, Nadia Maïzi

chaire modélisation prospective au service du développement durable

les cahiers de la chaire

« Energy sector contribution to regional climate action:

The case of Latin America »

Sebastien Postic, Sandrine Selosse, Nadia Maïzi

MINES ParisTech - PSL Research University
Centre for Applied Mathematics (CMA), France

Working Paper
N°2016-02-20

Working Paper
N°2016-02-20

contents

Energy sector contribution to regional climate action:

The case of Latin America

Sebastien Postic[1], Sandrine Selosse, Nadia Maïzi

MINES ParisTech - PSL Research University
Centre for Applied Mathematics (CMA), France

I - Introduction

The most optimistic Representative Concentration Pathway (RCP 2.6) in the fifth IPCC Assessment Report predicts a 0.3°C to 1.7°C global mean temperature change in 2100, putting natural species and systems at risk, possibly triggering large-scale irreversible natural damage, and strongly impacting human activities (IPCC, 2014). In South America and the Caribbean, a region representing a relevant share of global GHG emissions with a weight of 7.7% in 2011 (World Resources Institute, 2015), slightly more than its share of the world's population (6.9% in 2010), the latest estimates point to a 1.5% to 5% GDP loss by 2050 (Samaniego et al., 2014). Particularly, Brazil already ranks fourth in the world when it comes to national contributions to global warming (Matthews et al., 2014) and a strong increase in GHG emissions can be anticipated in the years to come throughout the region on a BAU basis (Carvallo et al., 2014; Fundación Bariloche, 2008; van Ruijven et al., 2015). In this context, quite logically, the region has a relevant role to play in mitigating global emissions.
No South American countries are included in Annex I of the United Nations Framework Convention on Climate Change (UNFCCC) and as such, before the Paris Agreement on climate change signed in December 2015 in Paris during the COP 21, they were not bound to any GHG quantified emission reduction. They had, however, been invited to voluntarily commit to Nationally Appropriate Mitigation Actions (NAMAs). Part of the Copenhagen Accord, NAMAs provide a flexible framework within which non-Annex I countries can pledge voluntary actions at an economy-wide or sectorial level, aimed at deviating from BAU emissions (Sharma and Desgain, 2014). The nature, quantification and implementation roadmap[1] of these NAMAs vary considerably across South America.

- Chile has pledged emission reductions of 20% by 2020, compared to a 2009 Business-As-Usual scenario (BAU); there is no quantified measure in its engagement letter concerning how this target will be met, and little description. Energy efficiency, renewable energies and AFOLU (Agriculture, Forestry and Other Land-Use) are specified as the main action sectors for these reductions.
- Brazil has based most of its pledge on quantified emission reductions in the field of deforestation and more generally the AFOLU sector. These sectorial reductions have been aggregated into an estimated national target of 36.6% to 38.9% emission reductions below a national baseline by 2020.
- Colombia has committed to 77% renewables in its installed electricity production capacity by 2020, and 20% biofuels in overall fuel consumption.
- Peru has pledged a 0% net deforestation rate by 2021, as well as a minimum of 33% renewable energy in all energy consumed in the country, and non-quantified measures for waste emissions reduction. The country has not quantified the overall impact of these pledges, but independent academics estimate that the measures should lead to a 41% GHG reduction compared to BAU (Hof et al., 2013).

Corresponding author:
MINES ParisTech, PSL University, CMA-Centre for Applied Mathematics,
Rue Claude Daunesse - CS10207, 06904 Sophia Antipolis, France
Email: sebastien.postic@mines-paristech.fr

[1] For an exhaustive compilation of theses pledges, see (UNFCCC, 2013)

With the exception of small countries such as Antigua and Barbuda, the rest of the continent has so far made no pledges to the UNFCCC. However, national communications emphasize national measures and strategies in:

- Argentina: energy efficiency programs, renewable energy including biofuels and hydrogen, forest management, solid waste management;
- Ecuador: by 2020,
  - 82% of oil in primary energy, down from 92% in 2011
  - At least 90% renewable electricity, 80% from hydropower
- Uruguay: the National Plan to 2015 aims at over 15% electricity from unconventional renewable sources
- Paraguay: the country has set reforestation targets and expressed its intention to expand energy-crop cultures.

This list is far from exhaustive for national targets and measures that are not bound to the UNFCCC.

The energy sector, the largest contributor to GHG emission, shows promising potential to achieve climate mitigation worldwide (Akimoto et al., 2010) and South American NAMAs consider it extensively. However, the potential of the South American energy sector may remain below world averages (Bassi and Baer, 2009; Borba et al., 2012; Di Sbroiavacca et al., 2015), because of an already-renewable energy mix, fast energy growth –the electrification rate jumped from 75% in 2009 to around 90% in 2012 in Peru and Bolivia (CIER, 2013, 2011) – and the use of energy as a tool for domestic and international policy (Colgan, 2014).

Given Latin America's regional specificities, what contributions can its energy sector make to the fight against climate change, and at what cost? This paper investigates this specific aspect of the energy-climate nexus in Latin America through the prism of ongoing climate negotiations. This analysis focuses on the climate commitment of Latin America pledged before the Intended Nationally Determined Contributions (INDCs) asked to publish through the 2015 United Nations Climate Change Conference held in Paris in December and which led to the signing of a historical global agreement on climate change. We use a bottom-up energy prospective model from the MarkAl/TIMES family with four contrasted scenarios for future climate policies in South America, presented in section 2. In section 3, we study the energy sector's contribution to meeting regional climate pledges and the evolutions that such a contribution implies. We start by considering the specific case of the power mix then expand our study to the whole total primary energy supply, underlining the role of Brazil and Chile in driving the energy transition in South America. We also consider the efficiency and impact of Peru and Colombia's national commitments and the links between the AFOLU sector, the energy sector and the fight against climate change in Latin America.

II - Methods and scenarios

2-1 - The T-ALyC model

The results presented and discussed in this paper are based on the T-ALyC model. T-ALyC, standing for TIMES para América Latina y el Caribe, (TIMES for Latin America and the Caribbean), is a multiregional model based on the TIMES paradigm for long-term energy prospective. This modeling approach developed under IEA's Energy Technology Systems Analysis Program (IEA-ETSAP) Agreement considers a bottom-up representation of the energy system and relies on linear optimization techniques to meet an exogenous energy service demand at the lowest possible discounted cost, over a given time horizon (typically 2010-2050). The energy system is explicitly represented through a few thousand energy processes and commodities and their individual features (efficiency, investment costs, O&M costs, emission factors, etc.). Demand satisfaction is subject to resource constraints (resource availability, extraction cost), technical constraints (physical balances, availability factors, process lifetimes, etc.) and non-technical constraints (market penetration limits, policy scenarios, environmental specifications, etc.). For more information on the TIMES paradigm and its implementation, please refer to (Loulou et al., 2005). TIMES models minimize the cost of delivering a given energy service through both investment in, and operation of, energy processes. The outputs of TIMES models are the evolution and final structure of the energy system, individual investment and operation costs for each modeled technology, process-related and fuel-related emissions, energy trade flows between model regions and with the rest of the world, and the marginal cost of political constraints such as emission pledges.

T-ALyC's technological description is inherited from the TIMES Integrated Assessment Model TIAM, a 15-region representation of the whole world's energy system, from resource extraction to end-use energy demands (Loulou and Labriet, 2008; Ricci and Selosse, 2013; Syri et al., 2008). The Reference Energy System is split into a module for fossil fuel extraction, a transformation module from primary to refined fuels (including biomass transformation), an energy conversion module for electricity and heat production, and 5 end-use demand sectors, as shown in Figure 1.

T-ALyC considers the entire Latin America and the Caribbean region, excluding Mexico (conforming with the current Central and South America region in TIAM). T-ALyC relies on an ad hoc disaggregation of the area into 10 sub-regions (cf. Table 1) to address region-specific issues including the role of hydropower and interrogations about its future development, the current and future role of biofuels in the energy mix, challenges, opportunities and time dynamics of regional integration and the climate change-energy nexus. T-ALyC thus emphasizes in its geographical structure the main geo-energy trends of the continent, which include among others the weight and diversity of Brazil, the strategic interconnecting role of Bolivia, Paraguay, Uruguay and Central America, and the diverging paths of Chile and Argentina. The base year for model projections is 2010 and the end horizon is 2050. This time span is divided into 6 time periods, then 6 representative time slices in each period (three seasons: Winter, Summer, Intermediate; two diurnal divisions: Day, Night).

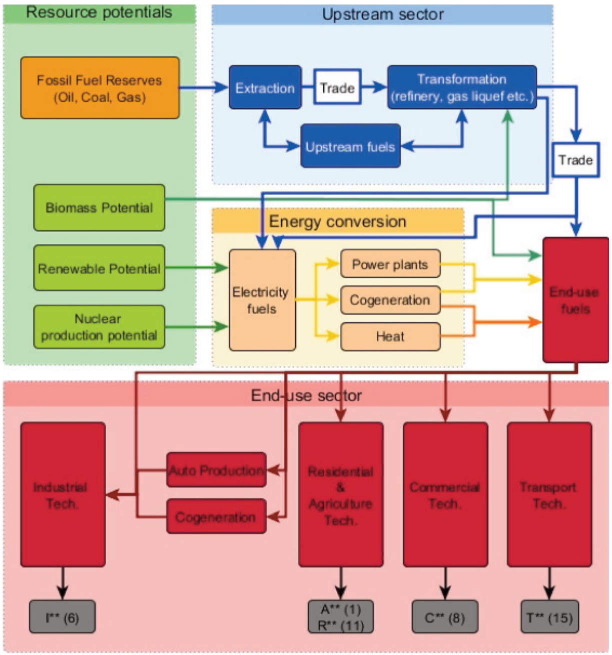

Figure 1: Schematic description of T-ALyC's RES

Energy potentials and end-use demands are calibrated based on a wide variety of sources, including (ALACER, 2013; Garcés et al., 2012; Global Energy Observatory, 2013; Hoornweg and Bhada-Tata, 2012; IEA, 2014; IER, 2006; IMF, 2014; Riegelhaupt and Chalico, 2009; Smeets et al., 2007; UN-DESA, 2012; UNEP, 2012; US-EIA, 2014; World Nuclear Association, 2008) and national sources. For this study, prices for energy commodity trade with the rest of the world are based on TIAM endogenous trade prices for the Central and South America region.

Region name	Region description
AND	Peru, Ecuador
ARG	Argentina
BPU	Bolivia, Paraguay, Uruguay
BSE	Brazil – South and Southeast administrative regions
BWC	Brazil – North, Northeast and Center administrative regions
CHL	Chile
COL	Colombia
CYC	Central America and the Caribbean
SUG	Suriname, Guyana, French Guyana
VEN	Venezuela

Table 1: T-ALyC geographical disaggregation

2-2 - GHG emissions and storage in T-ALyC

The emission structure in South America is quite different from the rest of the world. Brazil's national emission inventory reports GHG emissions from the energy sector that amount to only 15% of total national emissions (Brazilian Ministry of Science and Technology, 2010). By comparison, energy emissions for the European Union at the same date accounted for 80% of total emissions[2] (European Commission, 2014). This is mainly due to AFOLU: while in 2005 the Land-use, Land Use Change and Forestry sector in Europe was a net sink at 281 Mt CO2eq, the same sector in Brazil contributed up to 1,329 Mt CO2eq to national emissions. AFOLU emissions are thus not explicitly energy-related, yet they can impact the energy system through climate pledges. Faced with an emission-reduction objective, planners could choose to spend the money either on emission reductions in the energy-production sector, or on dedicated non-energy measures in e.g. the AFOLU or waste sectors. In the case of waste-linked emissions, emission reductions can even lead to energy production if landfill gases are retrieved and used for electricity generation. Available options in AFOLU include curbing deforestation, reforestation measures (re-establishment of a forest depleted by deforestation) and afforestation (creation of new forest areas). See (Smith et al., 2014) for a complete description of AFOLU's stakes in relation to global warming.

Such emissions are taken into account in our model through dedicated emission technologies, with an exogenous calibration based on national communications to the UNFCCC. Figure 2 below summarizes these contributions.

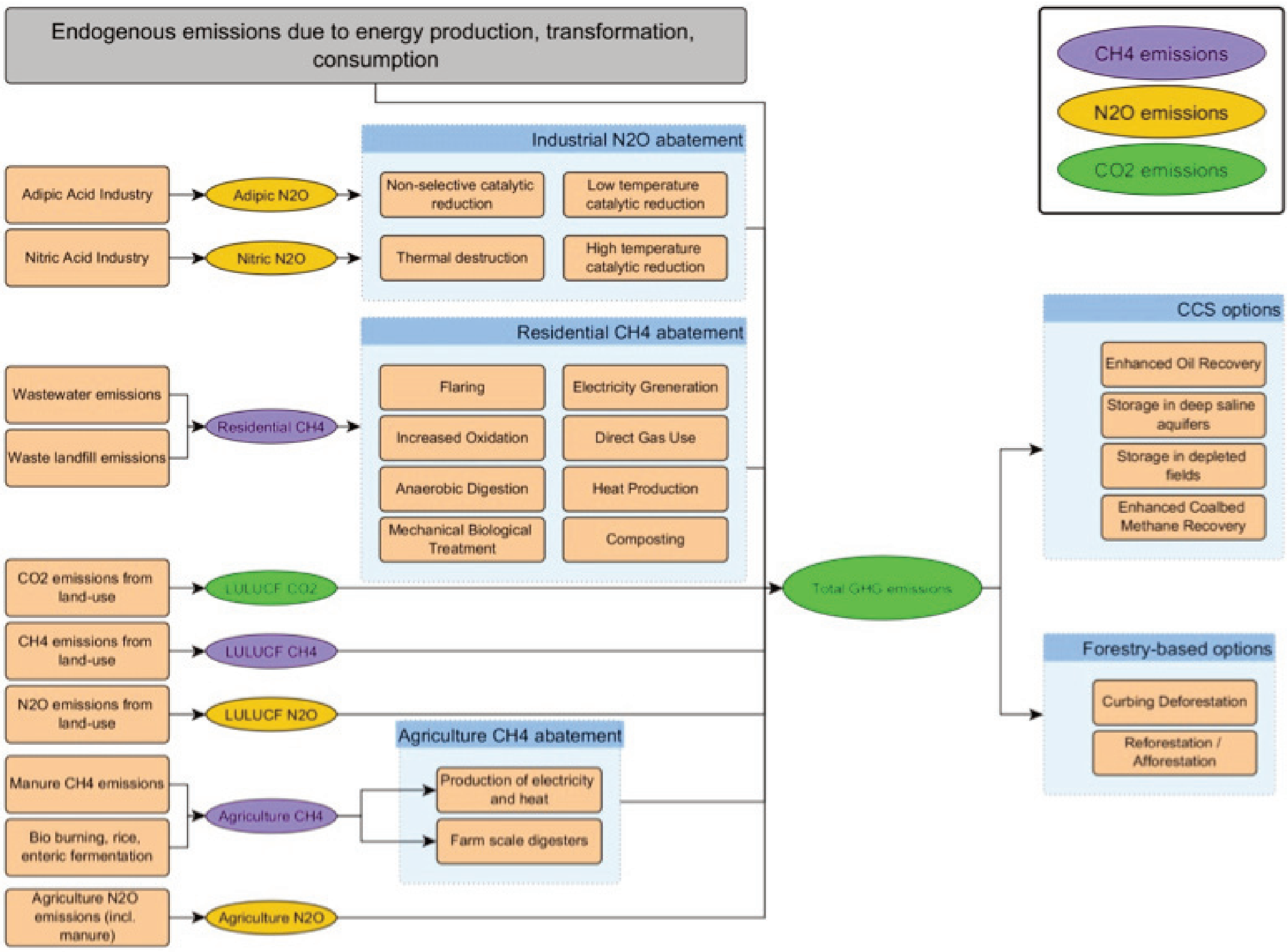

Figure 2: Accounting for non-energy GHG sources and sinks in T-ALyC

[2] Excluding AFOLU which is actually a sink rather than a source of CO2 emissions in Europe

While some emission reduction potentials are directly linked to the amount of emissions (e.g. thermal destruction of N2O emissions from the Nitric Acid Industry, or the fight against deforestation), some potentials are only partially related to such emissions – e.g. reforestation – or totally unrelated – e.g. storage in deep aquifers. In the case of forestry-based options, the potentials and associated costs were calibrated on external sources such as (Asner et al., 2014; Brazilian Ministry of Science and Technology, 2010; Elberg Nielsen et al., 2014; Gonzalez Arenas et al., 2011; Ministerio de Ambiente de Colombia, 2012; Ministerio de Ambiente del Perú, 2010; Ministerio del Ambiente del Ecuador, 2012, 2011; Ministerio del Medio Ambiente de Chile, 2011; Ministerio del Medio Ambiente de Uruguay, 2010; Nepstad et al., 2009; Secretaria de Ambiente de la República Argentina, 2007; Secretaria de Ambiente del Paraguay, 2011; Smith et al., 2014; Viceministerio del Medio Ambiente de Bolivia, 2009). We separate measures related to the fight against deforestation, calibrated on national baseline projections for deforestation, from afforestation-related measures, whose potential is linked to the available surface area. This area depends on the amount of forest-free land, and on the competition between afforestation and agriculture or other productive activities.

For all other options, we used TIAM costs and potentials (Ricci and Selosse, 2013) and regionalized the latter based on the T-ALyC regions' extraction potentials and surface areas. The potentials and costs of carbon storage technologies are detailed in Table 2 and Table 3 respectively. CCS option costs include transportation.

STORAGE OPTION	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Enhanced Oil Recovery	1,629	2,863	1,732	1,593	7,258	778	1,087	762	369	928
Storage in depleted fields	5,341	9,389	5,680	5,224	23,798	2,552	3,564	2,498	1,211	3,044
Enhanced coalbed meth. recov.	171	301	182	168	764	82	114	80	39	98
Deep saline aquifers	2,598	4,566	2,763	2,541	11,574	1,241	1,733	1,215	589	1,480
Curbing deforestation	15,506	1	4,905	1,272	12,053	0	3,764	0	0	0
Afforestation/reforestation	3,299	1,561	756	572	5,424	229	1,258	0	0	

Table 2: Cumulative storage capacity (2010-2050) for T-ALyC carbon storage options (MtCO2)

STORAGE OPTION	COST ($/TCO2)
Deep saline aquifers (onshore)	5.7
Deep saline aquifers (offshore)	9.3
Enhanced Oil Recovery and depleted fields injection (onshore)	5.1
Enhanced Oil Recovery and depleted fields injection (offshore)	8.2
Enhanced coalbed methane recovery	4.9
Curbing deforestation – Step 1	3
Curbing deforestation – Step 2	6
Curbing deforestation – Step 3	55
Afforestation – Step 1	10
Afforestation – Step 2	25
Afforestation – Step 3	45

Table 3: Cost of carbon storage technologies ($2000/tCO2)

2-2 - Climate scenarios

We investigate the impact of climate negotiations on the South American energy sector through 4 scenarios, namely “*Business-As-Usual*” (BAU), “*Brazil and Chile only*” (BraChi), “*All Nationally Adapted Mitigation Actions*” (NAMAs) and “*Quantified reductions for all*” (Red4All).

The *Business-As-Usual* scenario considers that no climate pledge is taken by any country. It allows us to present the key energy determinants of the continent, and serves as a comparison point for our climate pledge scenarios. We also use it to set the targets for climate scenarios, when such targets are defined as a reduction below a national emission baseline.

Brazil and Chile only is the least stringent climate scenario, considering only quantified reduction pledges for Brazil and Chile. For Brazil, our target is less stringent than that pledged in 2010, since the original objective was based on national BAU projections. We did not have access to this BAU, but the fight against deforestation improved dramatically between 2005 and 2010, so we can assume that part of the objective has already been met (emissions in 2010 and after in our own BAU are calibrated based on updated national inventories and are already much lower than in 2005). Also, Brazil’s constraint is written as an overall cap for the joint emissions of the two-region Brazil, meaning that the choice of where to reduce emissions is left to the model. Both Brazil and Chile’s targets are extrapolated to a 40% reduction below BAU in 2050.

All Nationally Adapted Mitigation Actions considers that UNFCCC pledges as described in the Introduction are implemented in Brazil, Chile, Colombia and Peru, plus a 30% deforestation reduction in Ecuador. Unlike for Brazil and Chile, the pledges for Colombia, Peru and Ecuador do not become stronger between 2020 and 2050. National voluntary policies that have not led to an NAMA pledge to the UNFCCC were not included in our modeling hypotheses.

Last, in *Quantified Reductions for all*, we consider that all countries make Chilean-like pledges on their future emissions. The only exceptions are Venezuela, Suriname, and Guyana. We consider that Venezuela would not adhere to any international agreements on climate[3] and the data we have on Suriname and Guyana is too poor to make any valuable projection concerning climate commitments. These assumptions are summarized in Table 4.

Region	2020 targets				2050 targets			
	BAU	BraChi	NAMAs	Red4All	BAU	BraChi	NAMas	Red4All
AND	-	-	NAMAs	-20%	-	-	NAMAs	-40%
ARG	-	-	-	-20%	-	-	-	-40%
BPU	-	-	-	-20%	-	-	-	-40%
BSE	-	-25%	-25%	-25%	-	-40%	-40%	-40%
BWC	-	-25%	-25%	-25%	-	-40%	-40%	-40%
CHL	-	-20%	-20%	-20%	-	-40%	-40%	-40%
COL	-	-	NAMAs	-20%	-	-	NAMAs	-40%
CYC	-	-	-	-20%	-	-	-	-40%
SUG	-	-	-	-	-	-	-	-
VEN	-	-	-	-	-	-	-	-

Table 4: Scenario assumptions for regional emission targets

[3] Venezuela’s current strong opposition to the US, as well as the fact that the country uses oil as a power tool for its domestic and international politics, make future commitments uncertain; in addition, Venezuela has not, to date, revised its First National Communication to the UNFCCC, submitted in 2005

III - Results and discussion: Impact of climate pledges on the Energy sector

Figure 3 shows the regional impact of climate scenarios in terms of emission reductions. Pledges by Brazil and Chile alone achieve a reduction of 1.08 GtCO2eq, equal to 17.5% below BAU projection, which is nearly half of the reductions achieved in the most stringent scenario. The NAMAs scenario results in an emissions reduction of 23.6% below BAU in 2050 (4.8 GtCO2eq instead of 6.2), yet 2050 emissions are still above 2010 figures, and the upward trend is not curbed. In the case of national commitments to reduce emissions by at least 40% from all countries (minus Venezuela), a 35.3% emission reduction below BAU is achieved in the region. 2050 GHG emissions are below 2010 levels, yet they climb up again from 2020 onwards, mainly due to Venezuelan emissions.

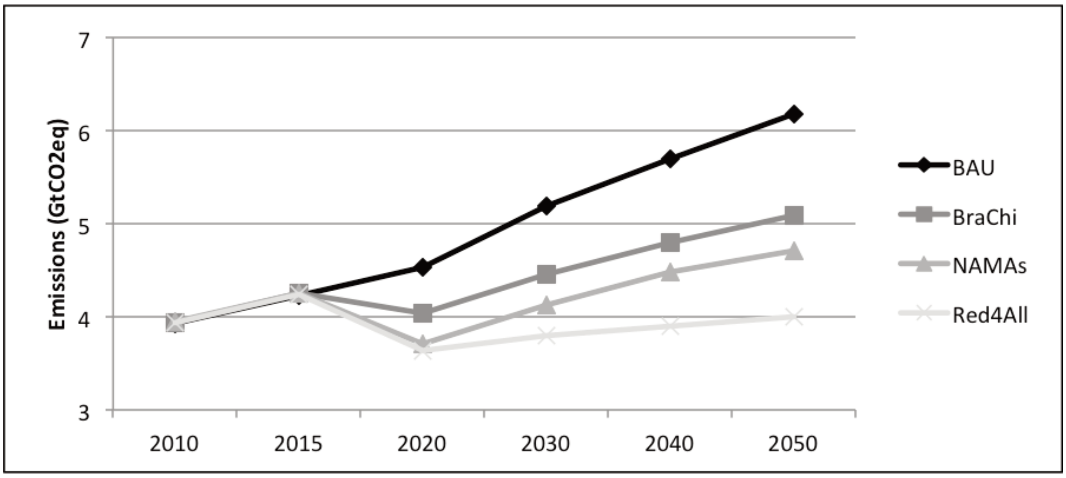

Figure 3: GHG emissions in CSA under BAU, NAMAs and Red4All scenarios

In the following paragraphs we detail this first insight, by comparing our Business-As-Usual projections with climate scenarios at sub-region and sector level. We first consider the power mix, then total primary energy production.

3-1 Impact of climate pledges on electricity

In 2012, South America already boasted a highly renewable electricity mix, with more than 60% of hydro-sourced electricity (CIER, 2013). The remaining electricity production was mainly made up of fossil fuels (gas, oil and coal) and nuclear power, leaving some room for improvement. Electricity generation is bound to almost double between 2010 and 2050, reflecting the region's forecasted strong growth, and this could, in principle, increase the share of carbon-emitting electricity sources in the energy mix, under BAU conditions. Figure 4, however, shows a completely different outcome in our projections. Despite a 92% increase in electricity generation, the share of fossil fuels drops sharply between 2012 and 2040. Similarly, while hydro production keeps increasing in absolute terms – from 677 TWh in 2010 to 1554 TWh in 2050, its share stabilizes in 2030, then starts dropping in the last two decades. The production gap is filled mainly by wind- and solar-based electricity production.

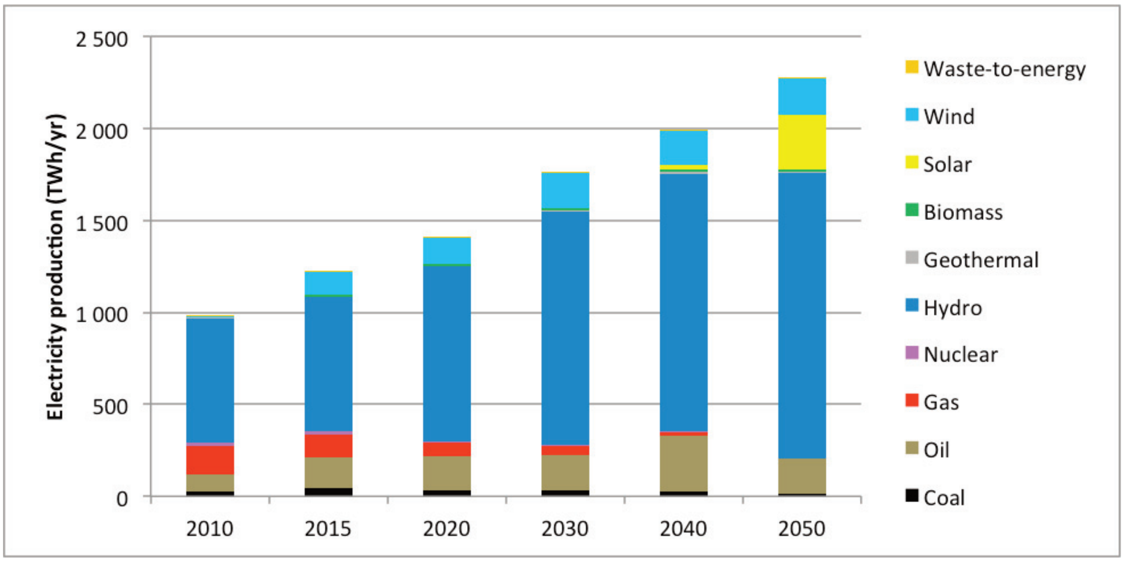

Figure 4: Electricity production in South America, 2012-2050 (Business-As-Usual)

The implications of such a result are already highly interesting: with no other assumption apart from cost minimization on a long-term horizon, the model already chooses green energies as the most interesting options for electricity production. This is partly due to the fact that this scenario occurs in an ideal world where long-term centralized planning is the rule. In practice, authors such as (Arango and Larsen, 2010) have stressed the fact that market forces and national policies in e.g. Argentina may lead to a carbonization of the electricity matrix in the years to come. However, our results imply that moving from a nearly 100% renewable power mix today to a 100% renewable mix tomorrow in South America is more about social acceptation and economic limitation than its lack of technical or economic potential.

Figure 5 displays the variations in power generation for our three climate scenarios compared to BAU, from the least stringent (BraChi) to the most stringent (Red4All). The impact of climate pledges on the energy sector appears clearly: the reliance on fossil fuels decreases in the three climate scenarios, and more so as time goes by. The amount of electricity generated under emission constraints is also slightly higher than in our BAU case, and so are electricity prices. Fossil fuels are replaced by hydropower, geothermal electricity and biomass-based production. The lower reliance on solar electricity in 2050 is mostly due to Brazil and Argentina and Colombia, and occurs for two main reasons. First, once oil has been completely removed from the electricity mix, the model installs BECCS technologies instead of solar panels to further decarbonize its electricity. Second, electricity prices rise slightly under climate constraint, and we reach a tipping point between decentralized PV and centralized, mid-price hydro production. This is a manifestation of the ‘razor edge effect’ of linear optimization models, as documented by e.g. (Labriet et al., 2010).

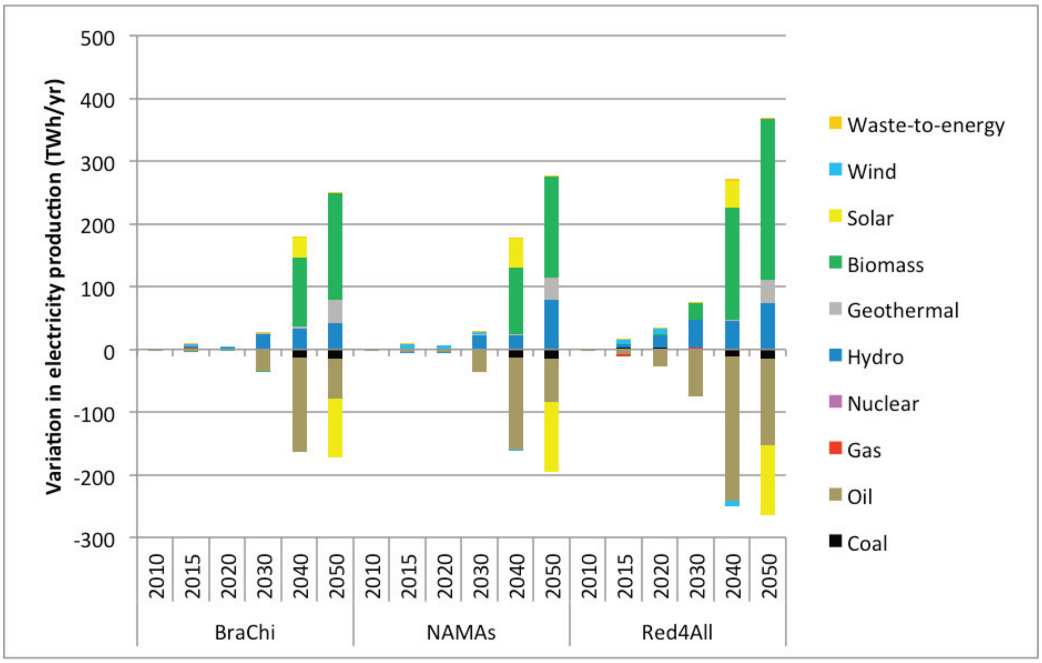

Figure 5: Modification of the power mix relative to BAU in BraChi, NAMAs and Red4All scenarios

We can detail this ‘razor edge’ effect for Colombia, in the NAMAs scenario. As a reminder, sectorial NAMAs were only proposed by Peru/Ecuador and Colombia (T-ALyC’s AND and COL regions). They lead to an additional emissions reduction of 380 Mt CO2eq in 2050 on the continent compared to BraChi, which is a further 6.2% below BAU. Figure 6 presents the evolution of the power mix, from BraChi to NAMAs, in three cost scenarios:

- The first one (NAMAs in the key on the figure) is the BAU cost scenario.
- In NAMAs_1%, both the investment and O&M costs for mid-price dam technology increase by 1%, to 1.290 $/W and 2.42 cts/W/yr, respectively.
- In NAMAs_2%, both the investment and O&M costs for mid-price dam technology increase by 2%, to 1.300 $/W and 2.44 cts/W/yr, respectively.

While this cost evolution does not impact the power mix in the AND region, the effect is quite disproportionate for COL: in the regular NAMAs scenario, most decentralized PV generation is displaced by hydropower, but this effect disappears completely with 2% higher dam costs. The cost structure is different for decentralized PV and centralized hydro production: in the decentralized PV case, investment costs are high and daily availability is constrained, but we consider no operation and maintenance costs, no transmission costs and/or losses. Investment costs are lower for hydropower, yet this technology is burdened by fixed operation and maintenance costs, transmission costs and transmission losses. However, the present value of the electricity generated by these two technologies in 2050 differs very little. Climate constraints increase the volumes and marginal costs of electricity production and favor the latter, as a consequence of the aforementioned ‘razor edge’ effect. In AND, NAMAs induce an increase in wind, solar and hydro energy in the electricity mix, while biomass is redirected towards heat production.

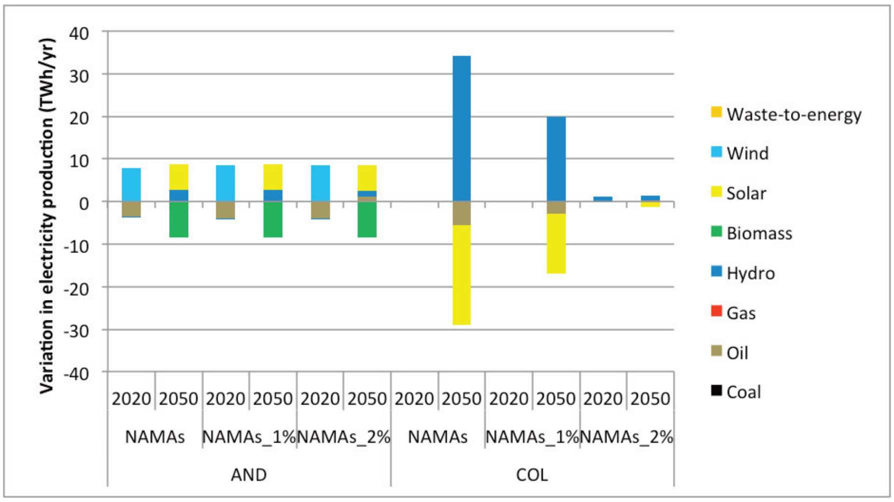

Figure 6: Deviation from the BraChi power mix in COL and AND in the NAMAs scenario, for three price scenarios

South America’s electricity mix thus contributes to regional emission targets by two means:

- First, by lowering the carbon intensity of the electricity produced: the reliance on fossil fuels is reduced by 75% in 2050 under the most stringent climate scenario, compared to BAU projection. Together with the introduction of BECCS technologies, 17% of the continent’s total electricity generation in 2050 shifts towards greener technologies, from a situation in which the electricity matrix was already quite virtuous.
- Second, by increasing the absolute amount of electricity produced, by up to 5% in 2050. Clean electricity competes here with other forms of energy for providing end-use energy services, mainly in the industry sector.

However, the added impact of the NAMAs scenario on the electricity mix is rather limited. This is mainly due to two factors: first, the only regions where NAMAs apply, namely AND and COL, together represent 11% of the electricity generated in South America in 2010 (15% in 2050). Second, unlike Chile and Brazil’s pledges, which are based on BAU projections, the electricity targets registered as NAMAs for COL and AND are already partially met under BAU conditions.

3-2 - Impact of climate pledges on primary energy consumption

3-2-1- The relevance of oil exports

When taking export-bound oil production into account, fossil fuels dominate primary energy production, constantly accounting for more than 70% of total production (Figure 7). In 2030, fossil fuels represent 80% of Latin American primary production; oil alone makes up 60% of this production, at 1,186 Mtoe.

The decrease in oil production after 2030 is owed to two factors (see Figure 8). First, Venezuelan crude oil exports, which make up the bulk of South American exports, are capped in our model at 24 PJ/year (approx. 573 Mtoe/yr) to avoid over-unrealistic export volumes, since global oil prices are static in this version of T-ALyC. Due to capacity expansion inertia, this threshold is reached in 2030, marking a clear break in the upward trend. Second, after two decades of oil bounty, exporting towards its neighbors and the rest of the world, Brazil itself starts importing oil, dragging Argentina and Uruguay along. The conjunction of those factors starts a downward trend for oil production in 2030. In the 2030-2050 period however, the rise of biomass and solar energy in the primary mix offsets this trend, leading to nearly stationary primary energy consumption between 2030 and 2050. However, primary solar energy as considered here is the incoming solar radiation before conversion into electricity[4]. As a consequence, the contribution of both biomass and solar energy to primary energy consumption is significantly larger than their actual output in terms of electricity/fuel/heat production.

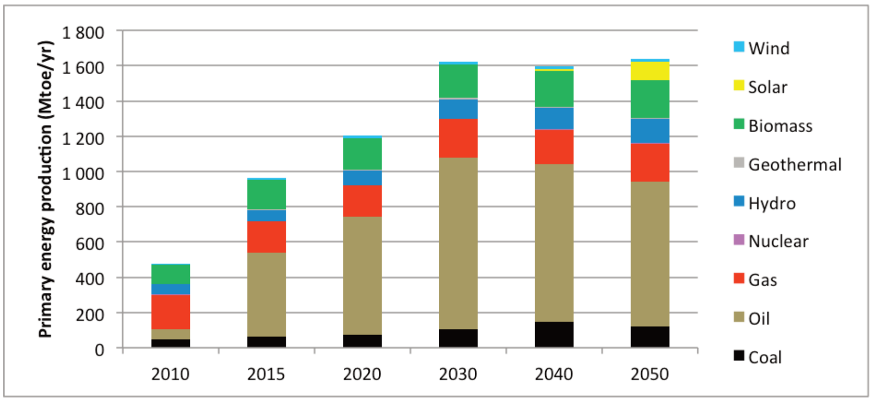

Figure 7: Primary energy production under BAU assumptions

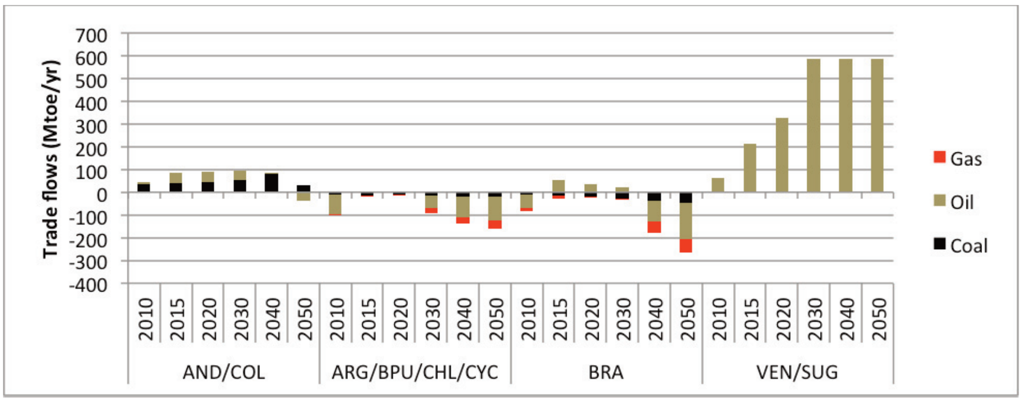

Figure 8: Latin America's fossil fuel trade with the rest of world (BAU)

[4] That is, without the energy losses incurred by solar panels/connecting lines. About 85% of this primary energy is lost in the conversion process.

The overwhelming majority of exported oil is crude, with few associated emissions. Nevertheless, climate pledges could still impact oil trade in South America, in three main ways:
Regardless of decisions and pledges from other world regions, penalizing the regional consumption of fossil fuels (through taxes, subsidies on green fuels, etc.) would indeed make them less competitive on the internal market, but would not impact exports' competitiveness. We can thus expect that the decrease in primary fossil energy production will at best be limited, with a shift from internal consumption to exports. Financing a green subsidy policy could even lead to an increase in oil production when the takeoff of renewables is bound to the redistribution of an oil rent, as studied by (Goldemberg et al., 2014).
Export volumes can be voluntarily reduced as part of a political volition to reduce the continent's contribution to global emissions. The Yasuni-ITT initiative, although unsuccessful, established an interesting case for this type of new cooperation framework (Pellegrini et al., 2014; Vallejo et al., 2015).
Export volumes can also drop as a result of international climate pledges, through their impact on global oil prices. The idea here is that international pledges would push renewable energy production and reduce global oil demand, thus bringing down oil prices. Venezuela produces heavy oil at relatively high costs (breakeven price estimated at USD 30, compared to USD 10 for Saudi Arabian wells) and would be among the first impacted by such a slowdown (its budget breakeven is considered by most analyses to be around or above USD 120). This assumption is confirmed by studies such as e.g. (Labriet et al., 2015). Another route could be a global border tax system, which would place oil exports on a level field with internal oil consumption (see e.g. (Keen and Kotsogiannis, 2014)) but have a detrimental effect on national industries.
The risk inherent to such a scenario would be that the no-longer-exported oil could be consumed within Latin America itself, replacing other renewable forms of energy production, starting with biofuels. As a first approximation of this issue, Figure 9 presents the evolution of the primary energy mix (net of trade) in a global context with oil prices 40% lower than their BAU value: solar energy all but disappears from the energy mix, and some gas is also replaced.

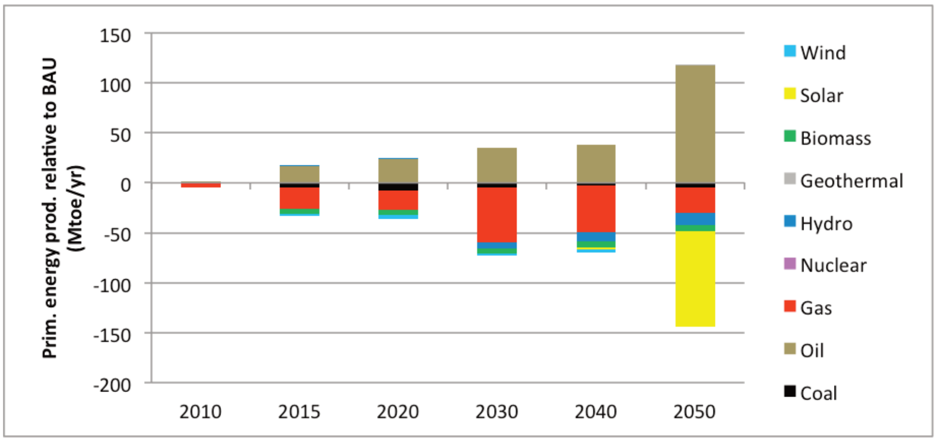

Figure 9: Change in primary energy consumption in CSA with low global oil prices
Brazilian pledges drive regional decarbonization

3-2-2- Brazilian pledges drive regional decarbonization

Figure 10 shows primary energy production in Latin America minus net energy trade. The total primary energy supply is multiplied by slightly more than 2.5 between 2010 and 2050. The share of oil is considerably reduced (from 60% down to 35% in 2030) and, conversely, the share of gas increases, mainly due to net gas imports from Brazil and Chile. The overall fossil fuel share remains below 70% of total primary consumption during the whole period, yet the mix is quite heavily fossil-fuel based. While the power sector is the first fossil fuel consumer in 2010, the demand for fossil fuels is increasingly driven by industry and transport (Figure 11), as electricity depends less and less on fossil fuels[5].

Beyond relatively virtuous power production, BAU projections for energy production in Latin America thus leave some room for GHG emission reductions, most of all in the transport and industry sectors. This decarbonization potential could be tapped through biofuel policies, energy efficiency measures, investment in clean generation and transportation, modal shift, etc. We consider here the impact of pledge reductions as is, that is, without choosing a particular sector to achieve emission reductions ex ante, and without implementing any other ad hoc scheme than those described in Introduction.

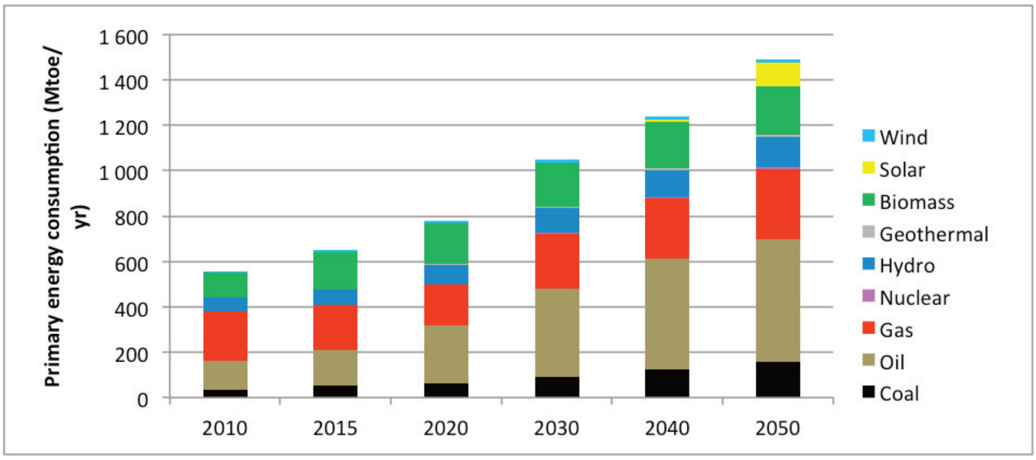

Figure 10: Primary energy consumption in BAU case – net of trade

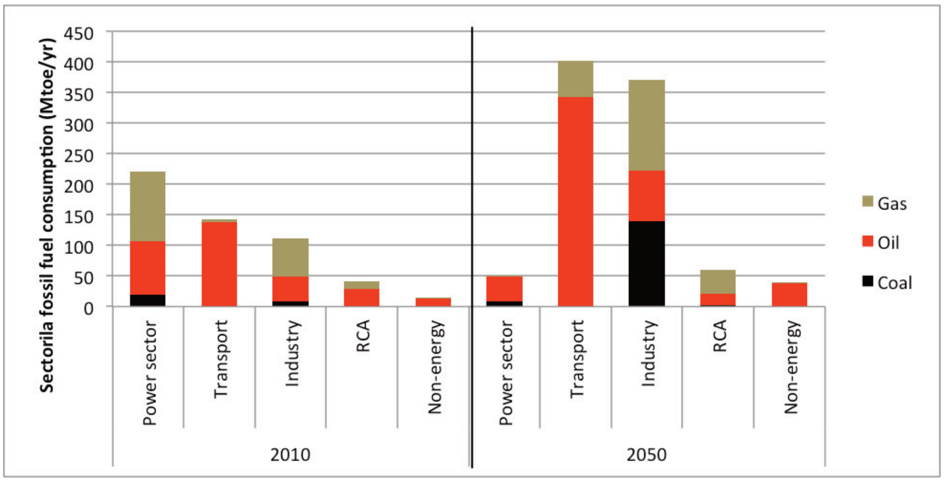

Figure 11: fossil fuel consumption in 2010 and 2050 (BAU)

[5] The elctric mobility option, although much discussed in literature, is actually not studied here, due to model limitations. It could bring interesting further research venues, though.

Figure 12 displays the variations in primary energy supply (net of trade) for the three climate scenarios compared to BAU, from the least stringent (BraChi) to the most stringent (Red4All). As for electricity, the decline in fossil fuels is noteworthy; a new element, however, is the higher penetration of natural gas in primary energy. Under climate constraints, the industry sector shifts from coal to gas for steam and process heat generation, most of all in the two Brazil regions (BSE and BWC). BSE's industrial sector still exhibits a strong reliance on biomass (bagasse) in the three scenarios.
Transport shifts heavily from oil-based fuels to biodiesel, with more than 40 Mtoe/yr new bio-based fuels in 2050 in the Red4All scenario. Both gasoline and diesel are impacted by this trend. All in all, a little more than 15% of the continent's 2050 primary energy production is transferred towards greener energy sources in the most stringent climate scenario, Red4All.

We now compare the BraChi scenario, where only Brazil and Chile's pledges are considered, with our BAU scenario. Figure 13 shows the impact of Brazil and Chile's pledges on energy trade in South America. BraChi pledges result not only in a decrease in national fossil fuel production and an increase in renewable-based energy production for the countries concerned; they also impact the rest of the continent through trade. BPU oil exports to Brazil and AND exports to Chile drop due to oil's reduced competitiveness in these two countries. Bolivia increases its gas exports to Brazil until 2040; however, this increase exhausts Bolivian low-cost gas reserves, leading Brazil to shift to global markets to import its oil in the last period (2050). Finally, and most importantly, Colombia slows down its coal exports to Brazil (and, to a lesser extent, Chile), preferring to export its coal out of South America. This impact is far from negligible, as the coal redirected towards global markets in 2040 and 2050 represents more than 70% of total Colombian coal exports to Brazil – which, in turn, represent nearly all of Brazil's coal consumption in 2050.

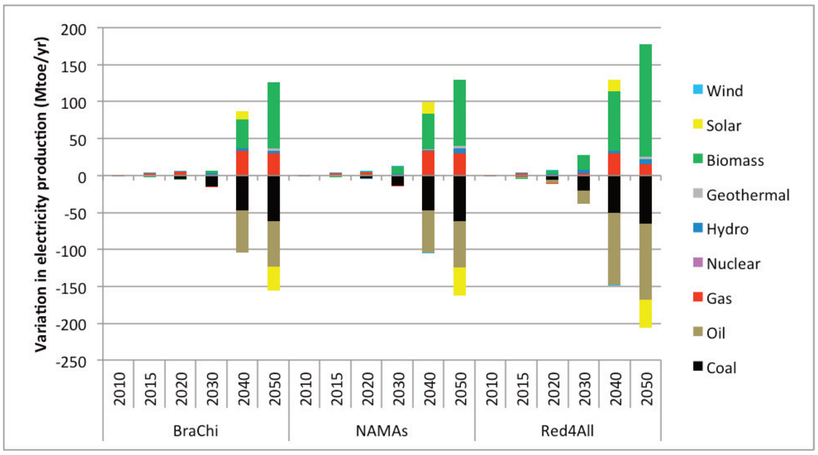

Figure 12: Modification of the primary energy mix relative to BAU in BraChi, NAMAs and Red4All scenarios

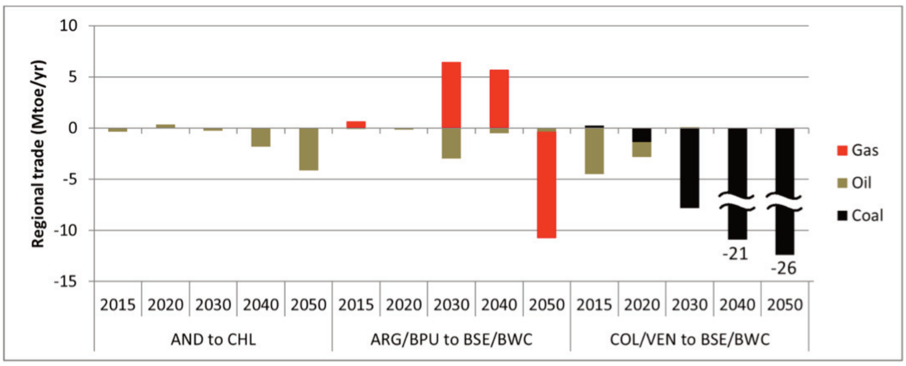

Figure 13: Impact of Brazil and Chile's pledges on intra-continental trade

A commitment by Brazil and Chile alone thus impacts the whole continent. Brazilian pledges to reduce emissions below BAU make fossil fuels less competitive in the country, and Brazil's economic weight[6] also drives their reduced competitiveness in neighboring countries, which translates into lower fossil fuel consumption inside South America itself and more exports outside the subcontinent.

[6] As a reminder, Brazil alone represents more than 40% of the continent's GDP, making it a giant in the region.

3-2-3- Sectorial targets: limited impact on energy

Let us now move to the NAMAs scenario. As already stated in paragraph 3.1, sectorial NAMAs have only been proposed by Peru/Ecuador and Colombia (T-ALyC's AND and COL regions). They lead to an additional emissions reduction of 380 Mt CO2eq in 2050 on the continent compared to BraChi, which is an additional 6.2% below BAU. However, this emissions reduction burden is not shared equally: for AND, emission reductions in 2050 under NAMAs assumptions represent 35.1% of all BAU emissions, while they account for 3.2% of BAU emissions in COL. There are two explanations for this difference:
First, Colombia's primary energy consumption is much less impacted by national NAMAs than Peru's (Figure 14). In the Andean region, bio-based energy production increases by up to 26.9 Mtoe/yr in 2050 compared to the BraChi scenario, that is, the increase represents 23% of AND total primary energy production in 2050 in BraChi[7]. On the other hand, primary energy production is only slightly impacted in 2050 in Colombia: the lower reliance on fossil fuels in 2050 (-3.03 Mtoe/yr) represents only a 2.8% deviation from Colombia's primary energy mix in BraChi. The main reason is that Colombia's NAMAs are already satisfied in our BAU projections, and more so in the BraChi scenario. This highlights one drawback of NAMAs compared to pledges for global reductions below a Business-as-Usual projection: while the latter always forces a change in the trend, the former may only follow the trend, with little if any impact.
Second, Peru and Ecuador's NAMAs include a strong commitment to reduce deforestation, while Colombia's national objectives in this area are not formalized as UNFCCC pledges. Beyond real but limited improvements through the energy mix, deforestation pledges account for 332 MtCO2eq avoided emissions in the AND region; in other words, 90% of AND's emission reductions result from the fight against deforestation. This highlights a second drawback of NAMAs: even NAMAs that effectively move the energy mix away from its BAU track may fail to deliver relevant GHG emission reductions in the specific South American context. On the positive side, though, well-designed NAMAs (here with deforestation-based targets) may deliver substantial emission reductions, without impacting strategic sectors such as energy production.
From the AND experience, we can infer that the energy sector may not have the highest emissions reduction potential in South America, due to the weight of forestry and agriculture in the continent's emissions. This assumption is detailed and confirmed in the next paragraph.

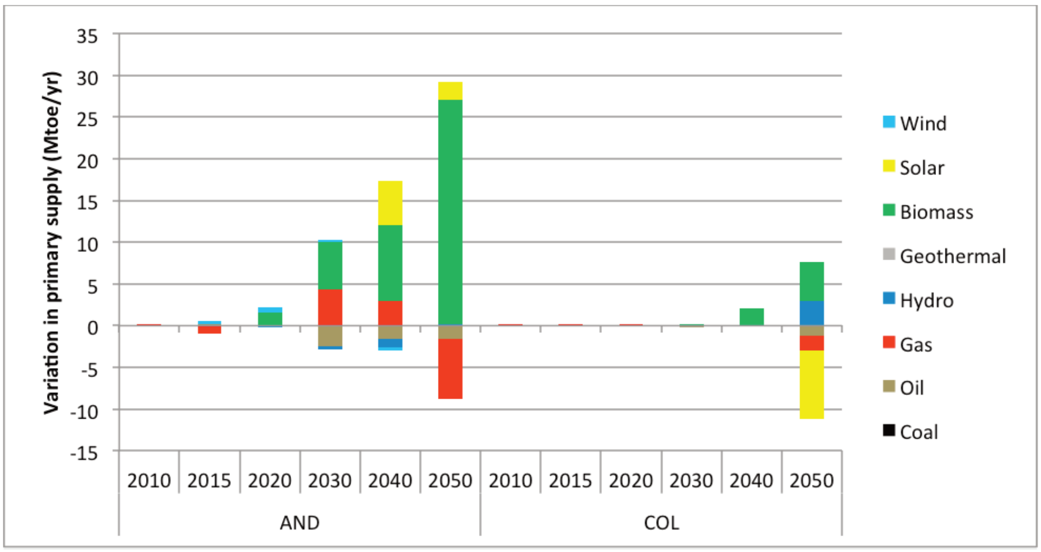

Figure 14: Primary consumption variation in AND and COL, from BraChi to NAMAs

[7] We consider NAMAs' impact by comparison with BraChi and not BAU to remove Brazil's influence on e.g. Colombia's coal exports.

3-3 - Non-energy emissions

In this last paragraph, we review the various sources and sinks for greenhouse gases modeled in T-ALyC and their contribution to GHG emission reduction, to contextualize the energy sector's contribution to fulfilling regional climate commitments.

Figure 15 shows GHG emissions, sector by sector, under the least stringent (BAU) and most stringent (Red4All) pledge scenarios, for the whole region. Figure 16 details GHG abatement in the Red4All scenario. Agriculture is the most emitting sector, totaling 47% of regional emissions in 2050 in the BAU scenario (2.9 GtCO2eq out of 6.17 GtCO2eq total emissions). The industry and transport sectors account for 37% of GHG emissions, while the energy sector (oil refining and electricity production) comes third with 12% of total emissions. The cumulative emission reductions achieved by energy, industry, transport, residential and commercial sectors together, through modal shift, renewable energy, carbon capture and storage, industrial efficiency, etc. represent 44% of total GHG abatement in 2050 under the Red4All scenario. Meanwhile, the remaining 56% are provided by AFOLU measures (mainly fighting deforestation, and reforestation). It is worth noting that due to the virtuous trend highlighted in paragraph 3.1, energy emissions already decrease in Business-as-Usual conditions, and that energy is the only sector showing this downward trend.

Figure 16 allows us to focus specifically on emissions absorption. The gray shading concerns absorption in the energy sector, green shows forestry options and red indicates GHG abatement options deployed in end-use sectors. The GHG abatement displayed here only relates to specific abatement-targeted measures as described in the legend, i.e. it does not consider emission reductions through e.g. fuel shift, demand reduction or efficiency improvements. As a consequence, the origin of emissions reduction in the transport and industry sectors is not captured well. The role of carbon storage in reducing energy emissions, however, appears clearly: together, enhanced Oil & Gas Recovery and Storage in depleted fields account for 200 MtCO2eq of emission reductions, i.e. more than 40% of all energy-bound emission reductions. Proper handling of flared gases adds another 36.5 MtCO2eq, with the remaining reductions due to further decarbonization of the energy mix. What also clearly emerges is the key role played by forestry in GHG emissions abatement, with 1,218 MtCO2eq emissions avoided by combating deforestation and promoting reforestation.

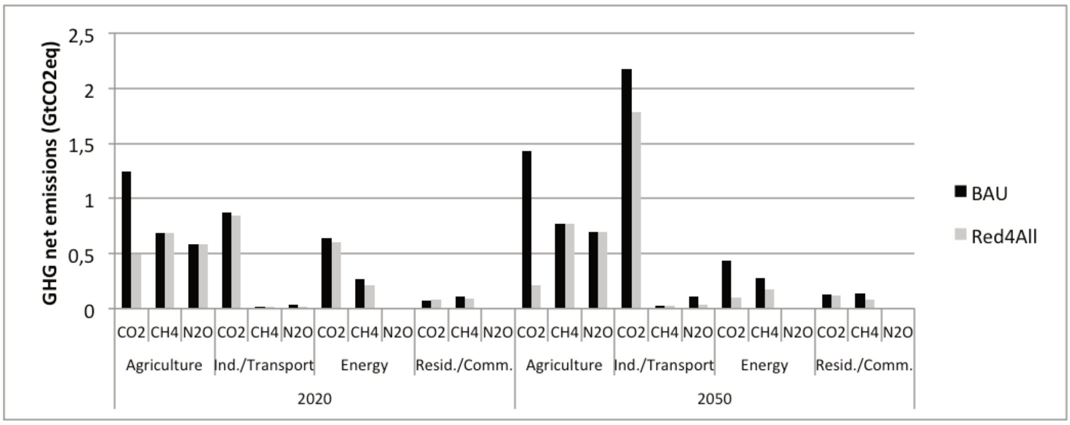

Figure 15: GHG net emissions by sector, under BAU and Red4All scenarios

[8]As a reminder, "Agriculture" in T-ALyC aggregates all AFOLU emissions.

The emissions reduction patterns considered here are radically different from the situation in Europe, where energy is foreseen as the main contributor to emissions reduction by 2050 (European Commission, 2011). In Central and South America, due to the overwhelming weight of AFOLU emissions, decarbonizing energy production and consumption is no longer the least expensive or most efficient tool to reduce GHG emissions. In fact, it would fall short of delivering more than 50% emission reduction, even at a prohibitive cost, and the target set here for 2050 –a 40% reduction– is not that far from that limit. GHG emission reductions in South America should therefore be considered from a very different viewpoint: energy is not the easiest way to achieve emissions reduction because it is not the main problem; forestry, on the other hand, remains a long-run carbon sink whose management options are the focus of active research, in terms of both technology and policy aspects (Arima et al., 2014; Asner et al., 2014). In the whole world, it is estimated that deforestation and forest degradation account for 17% of GHG emissions (IPCC, 2007) and these activities are already seen as a 'low-hanging fruit' in the fight against climate change (Stern, 2007), (Buizer et al., 2014). The present work tends to confirm this trend in the case of South America.

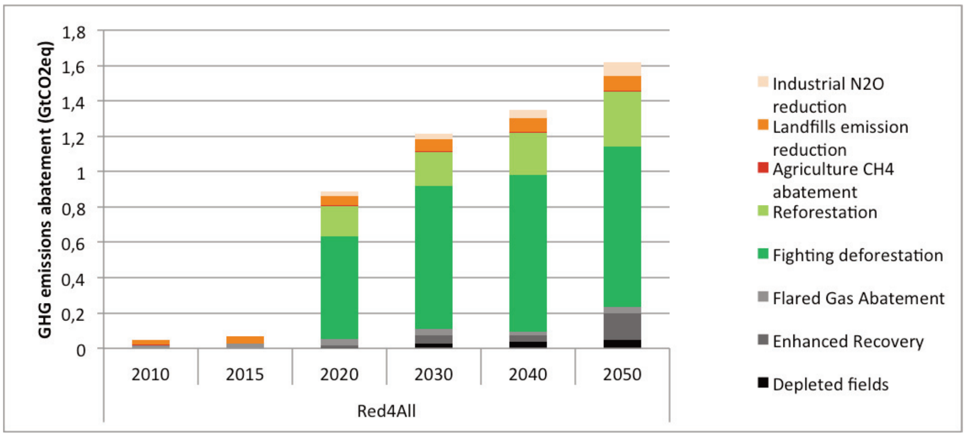

Figure 16: GHG capture and storage by sector (Red4All scenario)

IV - Conclusions and policy implications

This paper analyzed the energy sector's contribution to GHG emissions reduction in the UNFCCC framework. We outlined South America's energy sector potential for GHG abatement and the evolutions required to realize this potential.

We investigated this issue by means of a bottom-up, long-term optimization model, based on the TIMES paradigm yet specifically designed for South America: the TIMES-América Latina y el Caribe model, or T-ALyC. We compared four scenarios based on current national communications to the UNFCCC: a Business-As-Usual case, a BraChi scenario where only Brazil and Chile's pledges apply, a NAMAs scenario including all communicated NAMAs, and a hypothetic Red4All scenario where all countries except Venezuela would make Brazil-like commitments to reduce their GHG emissions by 40% below their baseline by 2050.

In our projections, energy accounts for nearly 20% of emission reductions in the most stringent (Red4All) scenario, with AFOLU providing 56% of these reductions in 2050. We find that energy is not the main contributor to emission reductions in South America for two main reasons: first, in our baseline, long-term economic optimization already leads to a decarbonization of the electricity sector. Further decarbonization can be achieved by shifting primary energy consumption by end-use sectors such as industry or transport. Second, the weight of deforestation and land degradation in the continent's GHG balance is considerable, even today, and it is more economically viable to curb this trend than to decarbonize a fairly clean energy mix. As a consequence, the impact of national pledges on the energy sector is real, yet feedback in terms of GHG abatement remains limited. We find that while pledges by Brazil and Chile impact the whole continent's energy trade by undermining oil and coal competitiveness, the added impact of Colombia's NAMAs is low, since national targets do not go far beyond our BAU trend. In Peru and Ecuador, NAMAs' impact on the energy system is more significant, yet forestry-aimed NAMAs alone deliver 90% of the sub-region's GHG abatement. However, the overall impact of NAMAs on Peru and Ecuador is strong, leading to significant emission reductions compared to BAU (35%). We also showed that a sustained drop in international oil prices due to e.g. an international climate agreement, could negatively impact the continent's emissions if South America did not commit to such an agreement, as oil exports would be redirected towards internal consumption and displace renewable energy sources. It is worth noting that such a drop would also have dramatic consequences on the Venezuelan economy, which relies quite heavily on oil exports.

The policy implications of these results, as developed in the results section, are many. We summarize four of them here. First, our results confirm the initial statement that South American climate-energy issues merit ad hoc modeling at a regional scale, since the countries on the continent share features that are quite different from the rest of the world, i.e. a highly renewable energy mix, very high renewable energy potentials along with high deforestation and degradation rates, which call for regional answers to regional issues. Second, in light of our results, that is, considering a first-order optimum that leaves aside energy markets and short-term decision-making, clean energy generation appears to be an economically viable option for South America. It is beyond the range of our modeling approach to take non-optimality factors into account to determine a second-best optimum; however, these first results suggest that heavy subsidies on fossil fuels such as those that exist in Venezuela, Argentina and Peru, may not move in the direction of economic optimality, in addition to their environmental inefficiency. Third, the significance of Brazil in South America's fight against climate change is incontestable, since its decisions already drive relevant changes in its neighbors' energy mixes. Last, and most important, we confirm that, in contrast to Annex I countries, energy cannot be the main focus of efforts to fight global warming in South America because it is not the continent's main problem. In South America, deforestation and land degradation are not only part of the climate issue: they make up the bulk of it.

The importance of deforestation also points to one limitation of our study: although we considered energy production and transformation in a very detailed way, our representation is more limited when it comes to AFOLU, due to the weak link between energy and e.g. reforestation. Further investigation of energy and AFOLU interactions in a climate context would require internalizing a bottom-up approach of the forestry sector, building on work such as e.g. (Overmars et al., 2014). Following another research line, integrating our results back into the global TIAM energy model would extend the intuitions we developed here on the role of oil in an interesting way, providing dynamic oil price feedback based on the possible results of climate talks, rather than a mere sensitivity analysis. Last, one major component of the climate-energy nexus that has not been touched on here is the adaptation issue: beyond mitigation, how to prepare a strongly renewable, climate-sensitive energy mix to tackle uncertain climate change effects? This issue is currently being worked on, and will form the basis of another publication.

V - Acknowledgements

This research was supported by the Chair Modeling for sustainable development, driven by MINES ParisTech, Ecole des Ponts ParisTech, and AgroParisTech, supported by ADEME, EDF, GRTgaz, SCHNEIDER ELECTRIC and the French Ministry of Ecology, Sustainable Development and Energy. The funding body was not involved in study design; collection, analysis and interpretation of data; the writing of the report; or the decision to publish.

VI - Bibliography

Akimoto, K., Sano, F., Homma, T., Oda, J., Nagashima, M., Kii, M., 2010. **Estimates of GHG emission reduction potential by country, sector, and cost.** Energy Policy, Large-scale wind power in electricity markets with Regular Papers 38, 3384–3393. doi:10.1016/j.enpol.2010.02.012

ALACER, 2013. **América Latina en cifras** - Asociación Latinoamericana del Acero.

Arango, S., Larsen, E.R., 2010. **The environmental paradox in generation: How South America is gradually becoming more dependent on thermal generation.** Renew. Sustain. Energy Rev. 14, 2956–2965. doi:10.1016/j.rser.2010.07.049

Arima, E.Y., Barreto, P., Araújo, E., Soares-Filho, B., 2014. **Public policies can reduce tropical deforestation: Lessons and challenges from Brazil.** Land Use Policy 41, 465–473. doi:10.1016/j.landusepol.2014.06.026

Asner, G.P., Knapp, D.E., Martin, R.E., Tupayachi, R., Anderson, C.B., Mascaro, J., Sinca, F., Chadwick, K.D., Higgins, M., Farfan, W., Llactayo, W., Silman, M.R., 2014. **Targeted carbon conservation at national scales with high-resolution monitoring.** Proc. Natl. Acad. Sci. doi:10.1073/pnas.1419550111

Bassi, A.M., Baer, A.E., 2009. **Quantifying cross-sectoral impacts of investments in climate change mitigation in Ecuador**. Energy Sustain. Dev. 13, 116–123. doi:10.1016/j.esd.2009.05.003

Borba, B.S.M.C., Lucena, A.F.P., Rathmann, R., Costa, I.V.L., Nogueira, L.P.P., Rochedo, P.R.R., Castelo Branco, D.A., Júnior, M.F.H., Szklo, A., Schaeffer, R., 2012. **Energy-related climate change mitigation in Brazil: Potential, abatement costs and associated policies.** Energy Policy, Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy 49, 430–441. doi:10.1016/j.enpol.2012.06.040

Brazilian Ministry of Science and Technology, 2010. **Second national communication of Brazil to the United Nations Framework convention on Climate Change**. Brasilia.

Buizer, M., Humphreys, D., de Jong, W., 2014**. Climate change and deforestation: The evolution of an intersecting policy domain.** Environ. Sci. Policy, Climate change and deforestation: the evolution of an intersecting policy domain 35, 1–11. doi:10.1016/j.envsci.2013.06.001

Carvallo, J.P., Hidalgo-Gonzalez, P., Kammen, D.M., 2014. **Envisioning a sustainable Chile.**

CIER, 2013. **Síntesis Informativa energética de los países de la CIER**, datos 2012.

CIER, 2011. **Síntesis informativa energética de los países de la CIER**, datos 2009.

Colgan, J.D., 2014. Oil, **Domestic Politics, and International Conflict**. Energy Res. Soc. Sci. 1, 198–205. doi:10.1016/j.erss.2014.03.005

Di Sbroiavacca, N., Nadal, G., Lallana, F., Falzon, J., Calvin, K., 2015. Emissions reduction scenarios in the Argentinean Energy Sector. Energy Econ. doi:10.1016/j.eneco.2015.03.021

Elberg Nielsen, A.S., Plantinga, A.J., Alig, R.J., 2014. **Mitigating climate change through afforestation: New cost estimates for the United States.** Resour. Energy Econ. 36, 83–98. doi:10.1016/j.reseneeco.2013.11.001

European Commission, 2014. **Sixth national Communication from the European Union under the UNFCCC.**

European Commission, 2011. **Roadmap for moving to a low-carbon economy in 2050**.

Fundación Bariloche, 2008. **Argentina: Diagnóstico, prospectivas y lineamiento para definir estrategias posibles ante el Cambio Climático.**

Garcés, P., Garcia, F., Parra, C., Preciado, V., Lim, **S.H., Franco, E., 2012. Potencial de Recursos Energéticos y Minerales en América del Sur: Coincidencias Jurídicas hacia una Estrategia Regional.**
Global Energy Observatory, 2013. Information on Global Energy Systems and Infrastructure [WWW Document]. globalenergyobservatory.org. URL http://globalenergyobservatory.org/ (accessed 8.4.14).

Goldemberg, J., Schaeffer, R., Szklo, A., Lucchesi, R., 2014. Oil and natural gas prospects in South America: Can the petroleum industry pave the way for renewables in Brazil? Energy Policy 64, 58–70. doi:10.1016/j.enpol.2013.05.064

Gonzalez Arenas, J.J., Etter Rothlisberger, A.A., Sarmiento López, A.H., Orrego Suaza, S.A., 2011. **Análisis de tendencias y patrones espaciales de deforestación en Colombia.** Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia.

Hof, A.F., den Elzen, M.G.J., Roelfsema, M., 2013. The effect of updated pledges and business-as-usual projec-

tions, and new agreed rules on expected global greenhouse gas emissions in 2020.** Environ. Sci. Policy 33, 308–319. doi:10.1016/j.envsci.2013.06.007

Hoornweg, D., Bhada-Tata, P., 2012. **What a Waste - A Global Review of Solid Waste Management.** The World Bank.

IEA, 2014. International Energy Agency - **World Energy Statistics** - 2013 Edition.

IER, 2006. **Institut für Energiewirtschaft und Rationelle Energieanwendung** - Review of resources and trade of fossil energy resources in the TIAM model.

IMF, 2014. **International Monetary Fund** - World Economic Outlook Database [WWW Document]. URL http://www.imf.org/external/pubs/ft/weo/data/changes.htm (accessed 6.17.14).

IPCC, 2014. **Summary for Policymakers, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability.** Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernemental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007. **Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.** Geneva, Switzerland.

Keen, M., Kotsogiannis, C., 2014. **Coordinating climate and trade policies: Pareto efficiency and the role of border tax adjustments.** J. Int. Econ. 94, 119–128. doi:10.1016/j.jinteco.2014.03.002

Labriet, M., Drouet, L., Vielle, M., Loulou, R., Kanudia, A., Haurie, A., 2015. **Assessment of the Effectiveness of Global Climate Policies Using Coupled Bottom-up and Top-down Models,** Climate Change and Sustainable Development. Fondazione Eni Enrico Mattei, Milano.

Labriet, M., Loulou, R., Kanudia, A., 2010. **Modeling Uncertainty in a Large scale integrated Energy-Climate Model,** in: Filar, J.A., Haurie, A. (Eds.), Uncertainty and Environmental Decision Making, International Series in Operations Research & Management Science. Springer US, pp. 51–77.

Loulou, R., Labriet, M., 2008. **ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Comput. Manag.** Sci. 5, 7–40. doi:10.1007/s10287-007-0046-z

Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. **Documentation for the TIMES model: Part I. Energy Technol. Syst. Anal.** Programme Available Http-www Etsap Orgdocumentation Asp.

Matthews, H.D., Graham, T.L., Keverian, S., Lamontagne, C., Seto, D., Smith, T.J., 2014. **National contributions to observed global warming.** Environ. Res. Lett. 9, 014010. doi:10.1088/1748-9326/9/1/014010

Ministerio de Ambiente de Colombia, 2012. **Plan Nacional de Restauración.**
Ministerio de Ambiente del Perú, 2010. **El Perú y el Cambio Climático.** Lima.
Ministerio del Ambiente del Ecuador, 2012. Línea Base de Deforestación del Ecuador Continental. Quito.
Ministerio del Ambiente del Ecuador, 2011. **Segunda Comunicación Nacional sobre Cambio Climático.** Quito.
Ministerio del Medio Ambiente de Chile, 2011. **Segunda comunicación nacional de Chile ante la convención marco de las Naciones Unidas sobre cambio climático.** Maval Chile, Santiago, Chile.
Ministerio del Medio Ambiente de Uruguay, 2010. **Tercera Comunicación Nacional del Uruguay a la Conferencia de la Partes en la Convención Marco de la Naciones Unidas sobre el Cambio Climático.** Montevideo.

Nepstad, D., Soares-Filho, B.S., Merry, F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D.G., Stickler, C.M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida, O., Stella, O., 2009. **The End of Deforestation in the Brazilian Amazon.** Science 326, 1350–1351. doi:10.1126/science.1182108

Overmars, K.P., Stehfest, E., Tabeau, A., van Meijl, H., Beltrán, A.M., Kram, T., 2014. **Estimating the opportunity costs of reducing carbon dioxide emissions via avoided deforestation, using integrated assessment modelling.** Land Use Policy 41, 45–60. doi:10.1016/j.landusepol.2014.04.015

Pellegrini, L., Arsel, M., Falconí, F., Muradian, R., 2014. **The demise of a new conservation and development policy? Exploring the tensions of the Yasuní ITT initiative.** Extr. Ind. Soc. 1, 284–291. doi:10.1016/j.exis.2014.05.001

Ricci, O., Selosse, S., 2013. **Global and regional potential for bioelectricity with carbon capture and storage. Energy Policy,** Special Section: Transition Pathways to a Low Carbon Economy 52, 689–698. doi:10.1016/j.enpol.2012.10.027

Riegelhaupt, E., Chalico, T.A., 2009. **Opportunities and challenges for biofuel production in Latin America: a**

forester's perspective. CIFOR.

Samaniego, J., Bárcena, A., Prado, A., Pérez, R., 2014. **The economics of climate change in Latin America and the Caribbean: Paradoxes and challenges. United Nations -** CEPAL.

Secretaria de Ambiente de la República Argentina, 2007. **Segunda Comunicación Nacional de la República Argentina a la convención Marco de las Naciones Unidas sobre Cambio Climático.**
Secretaria de Ambiente del Paraguay, 2011. **Segunda Comunicación Nacional - Cambio Climático.** Asunción.

Sharma, S., Desgain, D., 2014. **Understanding NAMA Cycle.**

Smeets, E., Faaij, A., Lewandowski, I., Turkenburg, W., 2007. **A bottom-up assessment and review of global bio-energy potentials to 2050**. Prog. Energy Combust. Sci. 33, 56–106. doi:10.1016/j.pecs.2006.08.001

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. **Agriculture, Forestry and Other Land Use (AFOLU)**, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Faraghani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.

Stern, N., 2007. **The Economics of Climate Change: The Stern Review.** Cambridge University Press.

Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H., Peltola, E., 2008. **Global energy and emissions scenarios for effective climate change mitigation—Deterministic and stochastic scenarios with the TIAM model.** Int. J. Greenh. Gas Control 2, 274–285.

UNDESA, 2012. **World Population Prospects, the 2012 Revision [WWW Document].** URL http://esa.un.org/unpd/wpp/ASCII-Data/DISK_NAVIGATION_ASCII.htm (accessed 8.20.14).

UNEP, 2012. **Global Chemicals outlook 2012 [WWW Document].** URL http://www.unep.org/pdf/GCO_Synthesis%20Report_CBDTIE_UNEP_September5_2012.pdf (accessed 5.8.14).

UNFCCC, 2013. **Compilation of information on nationally appropriate mitigation actions to be implementes by developing country Parties - Revised note by the secretariat.**

US-EIA, 2014. **Energy Information Administration - International Energy Statistics.**

Vallejo, M.C., Burbano, R., Falconí, F., Larrea, C., 2015. **Leaving oil underground in Ecuador: The Yasuní-ITT initiative from a multi-criteria perspective.** Ecol. Econ. 109, 175–185. doi:10.1016/j.ecolecon.2014.11.013

Van Ruijven, B.J., Daenzer, K., Fisher-Vanden, K., Kober, T., Paltsev, S., Beach, R.H., Calderon, S.L., Calvin, K., Labriet, M., Kitous, A., Lucena, A.F.P., van Vuuren, D.P., 2015. **Baseline projections for Latin America: base-year assumptions, key drivers and greenhouse emissions**. Energy Econ. doi:10.1016/j.eneco.2015.02.003

Viceministerio del Medio Ambiente de Bolivia, 2009. **Segunda Comunicacion del estado plurinacional de Bolivia ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático.** La Paz.

World Nuclear Association, 2008. **WNA Nuclear Century Outlook Data [WWW Document].** URL http://www.world-nuclear.org/WNA/Publications/WNA-Reports/nco/Nuclear-Century-Outlook-Data/ (accessed 4.23.14).

World Resources Institute, 2015**. CAIT 2.0: WRI's climate data explorer [WWW Document]**. World Resour. Inst. URL http://cait2.wri.org/wri?undefined (accessed 3.17.15).

chaire modélisation prospective au service du développement durable

les cahiers de la chaire

chaire@modelisation-prospective.com

contacts

Nadia MAÏZI
Directrice du Centre de Mathématiques Appliquées (CMA)

MINES ParisTech/CMA
Rue Claude Daunesse - CS10207
06904 Sophia Antipolis - France
T. +33(0)4 97 15 70 79

Mail: nadia.maizi@mines-paristech.fr

Jean-Charles HOURCADE
Directeur de la Recherche au Centre International de Recherche sur l'Environnement et le Développement (CIRED)

CIRED
Campus du Jardin Tropical
45 avenue de la Belle Gabrielle
94736 Nogent sur Marne cedex
T. +33(0)1 43 94 73 63

Mail: hourcade@centre-cired.fr

Working Paper
N°2016-02-20